



UNIVERSITI PUTRA MALAYSIA

**COLLOID-SURFACE CHARACTERISTICS AND AMELIORATION
PROBLEMS OF SOME VOLCANIC SOILS IN WEST SUMATRA,
INDONESIA**

DIAN FIANTIS

FP 2000 8

**COLLOID-SURFACE CHARACTERISTICS AND
AMELIORATION PROBLEMS OF SOME
VOLCANIC SOILS IN WEST SUMATRA,
INDONESIA**

DIAN FIANTIS

**DOCTOR OF PHILOSOPHY
UNIVERSITI PUTRA MALAYSIA**

2000



**COLLOID-SURFACE CHARACTERISTICS
AND AMELIORATION PROBLEMS OF SOME
VOLCANIC SOILS IN WEST SUMATRA, INDONESIA**

By

DIAN FIANTIS

**Thesis Submitted in Fulfilment of the Requirements for the
Degree Doctor of Philosophy in the Faculty of Agriculture
Universiti Putra Malaysia**

June 2000



DEDICATION

This thesis is dedicated to my beloved parents

Hj. Suarni

and

late H. Zubir Latif

who always supported and encouraged me to do the best.

**Abstract of thesis presented to the Senate of Universiti Putra Malaysia
in fulfillment of the requirements for the degree of
Doctor of Philosophy**

**COLLOID-SURFACE CHARACTERISTICS
AND AMELIORATION PROBLEMS OF SOME
VOLCANIC SOILS IN WEST SUMATRA, INDONESIA**

By

DIAN FIANTIS

June 2000

Chairman : Prof. Dr. J. Shamshuddin

Faculty : Agriculture, UPM

Co-chairman : Prof. Dr. E. Van Ranst

Faculty : Science, Ghent University, Belgium.

Andisols from elevational transects at Mt. Marapi and Mt. Pasaman in West Sumatra, Indonesia were studied to characterize their physico-chemical and mineralogical properties. These soils are developed under a udic, isothermic and isohyperthermic climatic regime. They have dark epipedons with high contents of organic carbon and low bulk densities ($< 0.9 \text{ Mg m}^{-3}$). All the nine pedons studied were found to meet the physical and chemical criteria of andic materials.

Major minerals in the sand fraction are quartz, plagioclase, hornblende, augite, hypersthene, olivine and volcanic glass. Some of the volcanic glass is coated with amorphous materials. Allophane, cristobalite, feldspars and halloysite

are major minerals in the clay fraction. Some soils contain imogolite. Halloysite exists as tubular crystals. Gibbsite is found in Mt. Pasaman soils, while opaline silica is present in the surface horizons of Mt. Marapi soils.

The P sorption characteristics of the soils were described using Langmuir and Freundlich equations. The Langmuir phosphorus sorption maxima ranged from 856 to 2,051 mg P kg⁻¹ and the Freundlich phosphorus sorption maxima ranged from 300 to 2,500 mg P kg⁻¹. Mt. Pasaman soils have higher P sorption than Mt. Marapi soils due to higher allophane content in the former soils. By using stepwise regression analysis, the combination of Al₀, Si₀, Fe₀ and Al_d predicted more than 88 % of the variation in the P sorption. The external P requirements were between 300 to 2,700 mg P kg⁻¹ for Mt. Marapi soils and between 2,300 to 7,800 mg P kg⁻¹ for Mt. Pasaman soils.

Superphosphate and Ca-silicate applications have some effects on the soils. pH₀ changed after these amendments were applied. Phosphate application lowered pH₀ and increased CEC. Application of Ca-silicate increased pH₀ initially. Later it decreased. Application of Ca-silicate at 120 t ha⁻¹ decreased P sorption by 96 % while the external P requirement was reduced by 90 %.

**Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Dokto Falsafah**

**SIFAT-SIFAT PERMUKAAN KOLOID DAN MASALAH AMELIORASI
PADA TANAH VULKANIK DI SUMATRA BARAT, INDONESIA**

Oleh

DIAN FIANTIS

June 2000

Pengurus : Prof. Dr. J. Shamsuddin

Faculti : Pertanian, UPM

Pengurus-bersama : Prof. Dr. E. Van Ranst

Fakulti : Sains, Ghent University, Belgium.

Sifat fizik-kimia dan mineralogi tanah Andisols daripada beberapa ketinggian di Gunung Marapi dan Gunung Pasaman di daerah Sumatra Barat, Indonesia telah dikaji. Tanah ini terjadi dalam keadaan regim kelembaban udic, isothermik dan isohipertermik. Tanah mempunyai epipedon yang gelap dengan karbon organik tinggi dan ketumpatan pukal rendah ($< 0.9 \text{ Mg m}^{-3}$). Kesemua 9 pedon yang dikaji memenuhi kriteria sifat fizik dan kimia andik.

Mineral utama yang dijumpai dalam bahagian pasir ialah kuarsa, plagioklas, hornblen, augit, hypersten, olivin dan gelas vulkan. Sebahagian daripada gelas vulkan dilapisi oleh bahan amorfus. Allophan, kristobalit, feldspars dan haloisit merupakan mineral utama yang terdapat dalam bahagian lempung. Ada beberapa

tanah mengandung imogolit. Halosit wujud dalam bentuk kristal tiup. Gibsit dijumpai dalam tanah Gunung Pasaman, manakala silika opal wujud di permukaan tanah Gunung Marapi.

Ciri-ciri jerapan P tanah dijelaskan dengan persamaan Langmuir dan Freundlich. Jerapan maksimum P bagi model Langmuir berkisar pada nilai 856 - 2,051 mg P kg⁻¹ dan jerapan maksimum P bagi Freundlich pula ialah 300 - 2,500 mg P kg⁻¹. Tanah Gunung Pasaman mempunyai jerapan P yang lebih tinggi jika dibandingkan dengan tanah Gunung Marapi. Dengan menggunakan regresi, kombinasi Al₀, Si₀, Fe₀ dan Al_d dapat meramalkan lebih 88 % daripada variasi jerapan P. Keperluan P ialah antara 300 ke 2,700 mg P kg⁻¹ untuk tanah Gunung Marapi dan antara 2,300 ke 7,800 mg P kg⁻¹ untuk tanah Gunung Pasaman.

Aplikasi superphosphat dan Ca-silikat mempunyai kesan kepada tanah. pH₀ berubah selepas aplikasi bahan ini. Aplikasi fosfat menurunkan pH₀ dan menaikkan KPK. Aplikasi Ca-silikat meningkatkan pH₀ pada mulanya. Kemudian ianya turun. Aplikasi 120 t ha⁻¹ Ca-silikat menurunkan jerapan P sebanyak 96 % manakala keperluan P menurun sebanyak 90 %.

ACKNOWLEDGEMENTS

This work hopes to contribute to our limited knowledge concerning the nature and properties of well-drained volcanic ash soils in the humid tropics, in general, and in the West Sumatra of Indonesia, in particular. This thesis is based on my intensive field and laboratory works in the last couple of years. The completion of this thesis would have been impossible without the assistance and direct involvement of so many kindhearted individuals. Thus, I am very much indebted to my present as well as to my previous mentors. I have no way of repaying such a debt except to express my sincerest gratitude.

Foremost, I am very grateful to my promoters, Prof. Dr. J. Shamshuddin, Deputy Dean, Faculty of Agriculture, UPM, Malaysia, and Prof. Dr. E. Van Ranst, Director, Laboratory For Soil Science, Ghent University, Belgium, for their strong support, patient guidance and for the very enriching and thought-provoking discussions and lectures. They were always there for us and provide everything we need in the laboratory. With them around, we, their students felt there was nothing we could not overcome even when the going became very tough. I benefited to a great deal from their long and extensive research experience on tropical soils.

To Assoc. Prof. Dr. Siti Zauyah Darus and Dr. Che Fauziah Ishak members of the Supervisory Committee for their comments and suggestions which contribute a lot to the improvement of the final manuscript. They also went to my sampling sites despite the difficult terrain and heavy rains in Mt. Marapi and Mt. Pasaman. There

were also few words of encouragement from those sessions, and I was always grateful for the time spent with them.

For the scholarship, I am indebted to Flemish Inter-University Council (VI.I.R), Belgium through Ph.D. Twinning Program between Universiteit Gent and UPM and Prof. Dr. G. Stoops, Director of ITC for the Land Resources Universiteit Gent, for accepting me in his project immediately after completing my M.Sc study. I am honored to be one of his students in Geological Institute of the University of Ghent Belgium. The administrative support from the Universitas Andalas Padang is also gratefully acknowledged.

Next, I wish to thank some of my previous teachers who have also contributed to and influenced my present understanding of the soil as a natural body. To Bapak Ir. I. N. Dt. R. Imbang of Universitas Andalas Padang from whom I received my first lesson in soil genesis and classification and guided me with my B. Sc. thesis. To Bapak Prof. Dr. Fachri Ahmad, former Rector of Universitas Andalas, now the vice governor of West Sumatra province who introduced me to volcanic ash soils and supported me ever since I was his student and encourage me to go further on my study abroad. I am also indebted to Prof. Dr. K. H. Tan of University of Georgia, Athens USA, for his guidance and valuable soil description during sampling and endless hours of discussion about many aspects of soil science.

I gratefully acknowledge the International Foundation for Science (IFS) of Sweden for the research grant on "Managing of volcanic ash soils from West

grateful to the Foundation for sponsoring my participation to the 16th World Congress of Soil Science in Montpellier, France, on August 21-27, 1998.

Thanks also to my friends, Mr. Somjate Pratummintra of Thailand, who always there for me and my sons. He is not only my best friend, he is also my son's best buddy. We really appreciate everything you have done for us during these last four years. We will miss your tom yam or other Thai's food. I am grateful to Mr. Renato Boniao of the Philippines, for his generosity in helping my English and smart discussion during our laboratory works and preparation of our final thesis. I am hoping that our friendship will last forever.

Many other people have also contributed to the completion of this work through their cooperation, help or advice. In UPM, Serdang they are: En. Azali Md Sab, Kak Nomi, Kak Fauziah (both from analytical and micromorphology labs.), En. Abdul Rahim and En. Jamil, En. Ramli and Bapak Ibrahim Shamsuddin. Acknowledgement is also due to Mrs. N. Vindevogel and Ms. M. Duchene for their helping hands during soil analyses in the laboratory of Soil Science, Ghent University. Also to Mr. J. De Weirde for facilitating all of the XRD. I sincerely honored Dr. G. Baert for his invaluable assistance during my tenure in Gent.

I wish to express my heartfelt thanks to my beloved husband 'Nelson' and our precious sons: Tito and Irfan for their patience and understanding. Finally, my deepest gratitude goes to my parents, sisters and brothers for their encouragement and help during my studies and away from home.

I certify that an Examination Committee met on June 8th, 2000 to conduct the final examination of Dian Fiantis on her Doctor of Philosophy thesis entitled "Colloid-Surface Characteristics and Amelioration Problems of Some Volcanic Soils in West Sumatra, Indonesia" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation. The committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

AZIZAH HASHIM, Ph.D.

Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

SHAMSHUDDIN JUSOP, Ph.D.

Professor \ Deputy Dean
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

ERIC VAN RANST, Ph.D.

Professor
Faculty of Sciences
Ghent University, Belgium
(Member)

SITI ZAUYAH DARUS, Ph.D.

Associate Professor \ Head of Department
Department of Land Management
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

CHE FAUZIAH ISHAK, Ph.D.

Faculty of Agriculture
University Putra Malaysia
(Member)

ESWARAN PADMANABHAN, Ph.D.

Faculty of Resource Science and Technology
Universiti Malaysia Sarawak
(External Examiner)



MOHD. HAZALI MOHAYIDIN, Ph.D.
Professor/Deputy Dean of Graduate School,
Universiti Putra Malaysia

Date **27 JUN 2000**



This thesis submitted to the Senate of Universiti Putra Malaysia and was accepted as fulfilment of the requirements for the degree of Doctor of Philosophy.



KAMIS AWANG, Ph.D.
Associate Professor
Dean of Graduate School,
Universiti Putra Malaysia

Date **13 JUL 2000**

I hereby declare that this thesis is based on my original work except for quotations and citations which, have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

signed



Candidate.

DIAN FIANTIS

Date: **26 JUN 2000**

TABLE OF CONTENTS

	Page
DEDICATION.....	ii
ABSTRACT.....	iii
ABSTRAK	v
ACKNOWLEDGEMENTS.....	vii
APPROVAL SHEETS	x
DECLARATION FORM	xii
LIST OF TABLES	xv
LIST OF FIGURES	xviii
CHAPTER	
I INTRODUCTION	1.1
Effects of Volcanic Ash on Soils	1.1
The Need for More Information on West Sumatra's	
Volcanic Ash Soils	1.2
Objectives of the Study	1.3
 II PHYSICAL ENVIRONMENT OF STUDY SITE	 2.1
Geographical Location of Volcanic Ash Soils	2.1
Geology of West Sumatra	2.3
Climate	2.9
Vegetation	2.13
 III LITERATURE REVIEW	 3.1
Classification of Volcanic Ash Soils	3.1
Characteristics of Volcanic Ash Soils	3.4
Physical Properties	3.4
Chemical Properties	3.5
Mineralogical Properties	3.10
Utilization of Volcanic Ash Soils	3.16
 IV MATERIALS AND METHODS	 4.1
The Soils for the Study	4.1
Soil Sampling	4.2
Soil Preparation and Place of Analyses	4.2
Methods of Analyses	4.2
Physical Analyses	4.2
Routine Chemical Analyses	4.4
Surface Reactivity	4.6
Charge Characteristics	4.8
Mineralogical Analyses	4.9
Laboratory Experiments	4.14

	Application of Calcium Silicate and Superphosphate	4.14
	Data Collection	4.14
V	RESULTS AND DISCUSSION	5.1
	Composition of the Parent Material of the Soils	5.1
	Polarized Microscopy of Sand Fraction	5.3
	Morphological Properties	5.6
	Soil Horizons	5.6
	Soil Color	5.7
	Soil Texture	5.8
	Structure	5.9
	Consistence	5.9
	Soil Classification	5.11
	Diagnostic Surface and subsurface Horizons	5.11
	Soil Taxonomy	5.15
	World Reference Base for Soil Resources (WRB)	5.17
	Mineralogical Properties	5.20
	Quantitative Analyses	5.20
	Selective Dissolution	5.20
	Total Elemental Analysis	5.45
	Qualitative Analyses	5.53
	X-ray Diffraction (XRD) Analysis	5.53
	Infrared Absorption Spectroscopy (IR)	5.68
	Differential Thermal Analysis (DTA)	5.73
	Scanning Electron Microscopy (SEM)	5.76
	Chemical Properties	5.83
	Surface Reactivity	5.97
	P Sorption Isotherm	5.113
	Surface Charge Properties	5.134
	Physical Properties	5.146
	Effects of Calcium Silicate and Superphosphate	
	Applications on the soils	5.169
	Point zero of charge (pH ₀)	5.169
	Soil pH	5.178
	Phosphate Sorption Isotherm	5.181
	Exchange Properties	5.201
VI	PRACTICAL IMPLICATIONS ON SOIL MANAGEMENT	6.1
VII	SUMMARY AND CONCLUSIONS	7.1
	REFERENCES	R.1
	APPENDICES	A.1
	BIODATA OF AUTHORS	B.1

LIST OF TABLES

Table		Page
2.1.	Climatic data of Mt. Marapi area	2.10
2.2.	Climatic data of Mt. Pasaman area	2.10
5.1.	Elemental composition of the parent materials.....	5.1
5.2.	Mineral distribution in sand fraction.....	5.4
5.3.	Requirements for the melanic fulvic, mollic, umbric and ochric horizons (Soil Survey Staff, 1998; FAO, ISRIC and ISSS, 1998)	5.13
5.4.	Identification of the diagnostic surface horizon according to WRB	5.14
5.5.	Family name of the studied soils	5.17
5.6.	Classification in the studied soils.....	5.18
5.7.	Acid oxalate dissolution and estimated content of allophane, imogolite and ferrihydrite in fine earth fraction	5.21
5.8.	Acid oxalate dissolution of sand particles and estimated content of allophane and ferrihydrite	5.25
5.9	Acid oxalate dissolution of silt fraction and estimated content of allophane and ferrihydrite	5.27
5.10.	Acid oxalate dissolution of clay fraction and estimated content of allophane and ferrihydrite	5.29
5.11.	Na-pyrophosphate dissolution in fine earth fraction	5.32
5.12.	DCB dissolution of the fine earth fraction	5.37
5.13.	Statistical analysis of extractable Si, Al and Fe	5.42
5.14.	Mean difference of Si, Al and Fe in the studied soils	5.44
5.15.	Total elemental composition of the fine earth	5.45

5.16.	Recalculated of total elemental composition of fine earth and some molar ratios after subtracting with H_2O , H_2O^+ and P_2O_5	5.47
5.17.	Recalculated of total elemental composition of fine earth and some molar ratios after subtracting with H_2O , H_2O^+ , P_2O_5 and short-range order constituents	5.48
5.18.	Surface reactivity parameters in the studied soils	5.98
5.19.	Correlation coefficients between surface reactivity parameters in the studied soils	5.99
5.20.	Correlation coefficients between P Retention and the surface reactivity parameters	5.112
5.21.	P sorption isotherm parameters of soils from Mt. Marapi	5.114
5.22.	P sorption isotherm parameters of soils from Mt. Pasaman	5.114
5.23.	Multiple regression analysis of the effect of various aluminium, iron oxide fractions and OH release on the phosphate sorption maximum of Langmuir isotherm	5.123
5.24.	Multiple regression analysis of the effect of various aluminium, iron oxide fractions and OH release on the P requirement for plant growth (PRP)	5.125
5.25.	Multiple regression analysis of the effect of various aluminium, iron oxide fractions and OH release on the phosphate sorption maximum of Freundlich isotherm (PSM)	5.132
5.26.	Correlation coefficient between surface charge properties parameters and soil components	5.138
5.27.	Particle-size distribution of the studied soils	5.147
5.28.	Correlation coefficients between soil constituents and particle size classes obtained by different methods	5.149
5.29.	Summary of statistical analyses between bulk density and soil constituents	5.158
5.30.	Particle density and porosity of the studied soils	5.159
5.31.	Water storage of the studied soils	5.164

5.32.	Effect of amendments on pH H ₂ O after 2 and 6 months	5.179
5.33.	Effect of amendments on Δ pH after 2 and 6 months	5.180
5.34	Equilibrium parameters of P sorption isotherm at 25 ⁰ C	5.183

LIST OF FIGURES

Figure		Page
2.1	A map showing the location of Mt. Marapi and Mt. Pasaman in the Barisan Mountain Range in Sumatra	2.2
2.2	A map showing the geology of Mt. Marapi and its surrounding area	2.6
2.3	A map showing the geology of Mt. Pasaman and its surrounding area	2.8
2.4	Precipitation and evaporation in Padang Panjang station	2.11
2.5	Precipitation and evaporation in Sukamenanti station	2.11
5.1	(A). Relationship between allophane in silt and fine earth ... (B). Relationship between ferrihydrite in silt and fine earth..	5.28 5.28
5.2	Relationship between Al_p/Al_o ratio with (A) allophane and (B) Al_p	5.33
5.3	Relationship between $(Al_p+Fe_p)/C_p$ and (A) allophane and Si_o content	5.34
5.4	Relationship between C_p and (A) organic carbon and (B) Al_p or Fe_p	5.35
5.5	Depth function of DCB extractable Al and Fe in (A) P I M, (B). P III M, (C) P VII P and (D) P IX P	5.38
5.6	Depth functions of four types of extractable Al in (A) P II M, (B). P V M, (C). P VI P and (D) P VIII P	5.40
5.7	Depth function of four type of extractable Fe in (A) P II M, (B). P V M, (C) P VI P and (D) P IX P	5.41
5.8	Relationship between $clay_r$ content and (A) CaO, (B) Na_2O and (C) K_2O contents	5.50
5.9	Relationship between clayr contents (A) SiO_2 , (B) Al_2O_3 and (C) Fe_2O_3 contents	5.51

5.10	XRD patterns of the silt fraction from P III M	5.54
5.11	XRD patterns of the silt fraction from P IX P	5.55
5.12	XRD patterns of the silt fraction from P V M	5.56
5.13	XRD patterns of the clay fraction from P I M	5.59
5.14	XRD patterns of the clay fraction from P V M	5.60
5.15	XRD patterns of the clay fraction from P IX P	5.63
5.16	Effect of chemical pretreatment on clay mineral XRD characteristics of Ah horizon, P I M	5.65
5.17	Effect of chemical pretreatment on clay mineral XRD characteristics of Ah horizon, P VIII P	5.66
5.18	Infrared spectra of the clay fraction from P I M	5.68
5.19	Infrared spectra of the clay fraction from P IX P	5.69
5.20	Effects of chemical and heat treatment upon clay mineral IR characteristics of Ah horizon, P I M	5.71
5.21	Effects of chemical and heat treatment upon clay mineral IR characteristics of Ah horizon, P VIII P	5.72
5.22	DTA curves of clay fraction from P II M	5.74
5.23	DTA curves of clay fraction from P VII P	5.75
5.24	Electron micrographs of four morphological type of volcanic glass (A) bubble, (B) curved platy, (C) fibrous and (D) berry-like	5.77
5.25	SEM image of amorphous surface coating of volcanic ash particles of Mt. Marapi (A) overview of samples, (B) particles partly coated, (C) fine-textured coating material and (D) details of C.....	5.79
5.26	Effect of ammonium oxalate dissolution on the surface of sand particles	5.80

5.27	An electron micrograph and EDX spectrum showing feldspars weathering to tubular halloysite	5.82
5.28	Behavior of pH with depth in the studied soils	5.84
5.29	Relationship between pH with allophane, Base Saturation (BS) and organic carbon	5.85
5.30	Relationship between Δ pH with (A) allophane, (B) Al_o , (C) ferrihydrite and (D) $Al_p + Fe_p$	5.87
5.31	Behavior of organic carbon (O.C) and total nitrogen with soil depth	5.89
5.32	Relationship between organic carbon and allophane content..	5.90
5.33	Relationship between total nitrogen and (A) organic carbon and (B) allophane	5.92
5.34	Forms and status of phosphorus in the southern toposequence of Mt. Marapi	5.95
5.35	Forms and status of phosphorus in the northern toposequence of Mt. Marapi	5.96
5.36	Forms and status of phosphorus in the Mt. Pasaman soils	5.97
5.37	Effect of ammonium oxalate and Na-pyrophosphate dissolution on soil pH (A) after 2 minutes and (B) after 24 hours	5.102
5.38	Relationship between OH release and (A) allophane, (B) organic carbon and (C) ferrihydrite	5.105
5.39	Relationship between OH release and (A) oxalate extractable Al, (B) pyrophosphate extractable Al and (D) DCB extractable Al	5.106
5.40	Relationship between P retention and (A) oxalate extractable Al, (B) oxalate extractable Si	5.108
5.41	Effect of ammonium oxalate dissolution on P retention	5.110
5.42	Relationship between P retention and (A) pH NaF, (B) OH release and (C) fluoride reactivity	5.112

5.43	Amount of P adsorbed with increasing concentration of soil from P II M	5.117
5.44	Amount of P adsorbed with increasing concentration of soil from P V M	5.117
5.45	Amount of P adsorbed with increasing concentration of soil from P VIII P	5.117
5.46	P sorption isotherm of soil in P II M according to Langmuir equation	5.119
5.47	P sorption isotherm of soil in P V M according to Langmuir equation	5.119
5.48	P sorption isotherm of soil in P VIII P according to Langmuir equation	5.119
5.49	Relationship between P sorption maximum (PSM) with (A) allophane and (B) organic carbon	5.120
5.50	Relationship between P sorption maximum with (A) oxalate extractable Al, (B) DCB extractable Al and (C) Pyrophosphate extractable Al	5.122
5.51	Relationship between P sorption maximum (PSM) of Langmuir equation with OH release after (A) 2 minutes and (B) 24 hours	5.123
5.52	Relationship between P requirement and (A) oxalate extractable Al and (B) oxalate extractable Si	5.126
5.53	Relationship between P requirement and (A) allophane and (B) organic carbon	5.127
5.54	P sorption isotherm of soil in P II M according to Freundlich equation	5.129
5.55	P sorption isotherm of soil in P V M according to Freundlich equation	5.129
5.56	P sorption isotherm of soil in P VIII P according to Freundlich equation	5.129

5.57	(A). PSM according to Langmuir and Freundlich isotherms... (B). Relationship between PSM Langmuir and Freundlich isotherms	5.131
5.58	Relationship between CEC with (A) organic carbon and (B) allophane	5.135
5.59	Contribution of organic and inorganic matter on CEC value from (A) surface and (B) subsurface horizons	5.136
5.60	Relationship between sum of basic cations and allophane	5.138
5.61	Relationship between sum of basic cation and (A) oxalate extractable Al, (P) pyrophosphate extractable Al and (C) DCB extractable Al	5.140
5.62	(A). Comparison of sum of basic cations between compulsive exchange and NH ₄ OAc methods (B). relationship between these two methods	4.142
5.63	Relationship between pH _o and allophane (A) before and (B) after oxalate dissolution	5.145
5.64	Relationship between clay resin with (A) ferrihydrite, (B) Al _d + Fe _d ; clay hmp with (C) allophane and (D) organic carbon	5.149
5.65	Relationship between silt resin with (A) ferrihydrite, (B) Al _d + Fe _d ; clay hmp with (C) organic carbon and (D) Al _d +Fe _d	5.151
5.66	Relationship between clay dispersion index hmp/resin with (A) allophane, (B) organic carbon; clay hmp with (C) allophane and (D) organic carbon	5.154
5.67	Distribution of the bulk density in the studied soils	5.156
5.68	Relationship between bulk density and (A) organic carbon, (B) allophane, (C) Al _o + Fe _o and (D) Al _p + Fe _p	5.157
5.69	Relationship between particle density and (A) allophane and (B) organic carbon	5.160
5.70	Relationship between total porosity and (A) organic carbon and (B) allophane	5.162

5.71	Relationship between available water and (A) allophane, (B) organic carbon, (C) bulk density and (D) ferrihydrite	5.166
5.72	Soil water profiles and distribution of water storage in (A) P I M, (B) P II M, (C) P VIII P and (D) P IX P	5.167
5.73	Relationship water content at 1500 kPa and (A) allophane, (B) organic carbon, (C) ferrihydrite and (D) bulk density.....	5.168
5.74	Effect of Ca-silicate application and incubation time on pH_o ..	5.170
5.75	Effect of P fertilizer application and incubation time on pH_o ..	5.171
5.76	Effect of Ca-silicate and P Fertilizer application on pH_o	5.176
5.77	Relationship between P sorption maximum (k_1) with pH_{H_2O}	5.185
5.78	Relationship between Ca-silicate and binding energy	5.185
5.79	Effect of Ca-silicate application on the amount of P sorbed needed to provide 0.2 ppm P in soil solution	5.187
5.80	P sorption isotherm of the incubated soil from P II M.....	5.188
5.81	P sorption isotherm of the incubated soil from P V M.....	5.189
5.82	P sorption isotherm of the incubated soil from P VI P.....	5.190
5.83	P sorption isotherm of the incubated soil from P VII P.....	5.191
5.84	Langmuir P sorption isotherm of the incubated soil from P II M.....	5.192
5.85	Langmuir P sorption isotherm of the incubated soil from P V M.....	5.193
5.86	Langmuir P sorption isotherm of the incubated soil from P VI P.....	5.194
5.87	Langmuir P sorption isotherm of the incubated soil from P VII P.....	5.195
5.88	Freundlich P sorption isotherm of the incubated soil from P II M	5.197